Really Useful Conceptual Models: Metaphors, Censorship and Negotiated Knowledge

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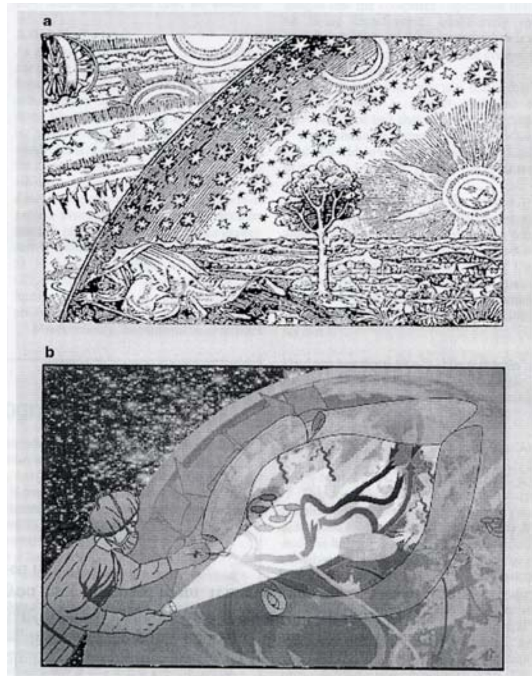


Figure 1 **A tale of two revolutions.** a, The shock of the Enlightenment as expressed in a (probably apocryphal[28]) fifteenth-century woodcut. b, 'Earth-system' diagnostics in the twenty-first century.

What is a conceptual model?

- There is no sense in which science can be said to be equivalent with reality. It must be perpetually a picture or model of reality. Quantification is the scientific process of building a metaphoric or conceptual basis for understanding the complexities of reality.

- Conceptual models are then simply socially negotiated pictures of the universe that inform the ongoing life of society (Christie 1990).

- *Concept* defined by Webster as

  "A general understanding derived from specific information"

- *Model* defined by Webster as

  "a small object usually built to scale that represents another often larger object" or " a tentative description of a system that accounts for all its known properties."

- Thus, a *conceptual model* can be operationally defined as

  "a generalized reduced-form description of the structure and function of a larger system that is excogitated from scale-dependent information (Plumb 2003)"

  "a visual or narrative summary that describes the important components of an ecosystem and the interactions among them (NPS 2003)"

How does one devise a useful conceptual model?

- Regardless of the format (table, schematic, narrative), developing a conceptual model involves selecting a particular abstraction of reality and fitting our reliable knowledge into that construct or picture.

- One must first identify the intended outcomes of using the conceptual model and then employ basic guiding principles of *relevance, reliability*, and *censorship* to devise a model or series of models that efficiently achieves the objective.

Relevance: Conceptual abstraction must be relevant to audience and scale.

Audience: Decide if the purpose of the conceptual model is to inform or influence, or both.

Scale: It is crucial to be able to identify the spatial and temporal scales that are of interest and relevant to outcomes.

Reliability: Conceptual abstraction must be underpinned with reliable knowledge.

Censorship: Conceptual abstraction must avoid over-simplification or over-sophistication.

- Employ a deliberate step-wise conceptual model formulation process (adapted from Grant et al. 1997).

1. State the model objectives.
2. Bound the system of interest.
3. Categorize discrete model components within the system of interest.
4. Articulate the relationships among the components of interest.
5. Represent the conceptual model.
6. Describe the expected pattern of model behavior.

What does the NPS Vital Signs Monitoring Program need from conceptual models?

Primary outcomes include both knowledge and action:

1. Comprehend the relevant structure and function of multiple levels of ecological organization of important park ecosystems (Knowledge).

    2. Translate understanding of ecological organization through deliberate and transparent decision support systems to identify the vital signs (ecological indicators) of environmental health in parks (Action).

3. Comprehend the range of natural (e.g. evolutionary) variability and ecological thresholds of dynamic "vital" ecological parameters (Knowledge).

    4. Translate understanding of thresholds of natural variability into deliberate and transparent long-term monitoring protocols capable of adequately detecting important departures from natural range of variability (Action).

5. Comprehend the range of anthropogenic-induced ecosystem variability that overlays the range of natural (e.g. evolutionary) variability and ecological thresholds of dynamic "vital" ecological parameters (Knowledge).

6. Translate understanding of anthropogenic-induced ecosystem variability into deliberate and transparent adaptive management alternatives for park managers to attempt mitigation (Action).

<u>What types of conceptual models are there?</u>

<u>*Narrative conceptual models*</u> are generally articulated in alpha & numeric form as informal or formal hypotheses, in a few sentences, formulae, or combinations of both. Extended narrative (e.g. single or multiple paragraphs) invariably encompass multiple tiered or linked conceptual models.

Example of informal narrative conceptual model:

> "Wolves in Yellowstone National Park, along with other carnivores, will regulate elk at lower density than during the previous wolf-free period, resulting in a "trophic cascade" of top-down effects on herbivores and vegetation (Boyce 1999)."

Example of formal narrative conceptual model:

> Wolf numerical response
> H1: Wolf population density in Yellowstone National Park will be limited by preferred prey biomass. Alternatively, wolf density might be limited by total prey biomass, territoriality or disease. W = *fn*(N, W, D) where W is the number of wolves, N is the number of elk, D is disease prevalence, and *fn* is the functional response of wolf population density (Boyce 1999).

Figure 1. Example of a formal equational narrative conceptual model.

$$m(C) = \frac{\sum_{j,k} m_1(A_j) \cdot m_2(B_k)}{1 - \sum_{j,k} m_1(A_j) \cdot m_2(B_k)} \times \frac{\text{when } A_j \cap B_k = C}{\text{when } A_j \cap B_k = \phi} \quad (1)$$

where m_1, m_2 and $m(C)$ are, respectively, basic probability assignments for focal elements A_j, B_k and combined evidential support for the subset C over the same frame of discernment. In this case, the theory of evidence (Shafer, 1976) also provides us the following relationships:

$$\text{Belief}\{S\} = m(S) \quad (2)$$

$$\text{Belief}\{S'\} = m(S') \quad (3)$$

$$\text{Ignorance} = m(S, S') = 1 - m(S) - m(S') \quad (4)$$

<u>*Tabular conceptual models*</u> generally present an array of ecosystem components in some form of a row-column structure, and can vary in complexity depending on the absolute number of cells presented (see Figure 2 and 3). In Figure 2, Heathcote (1998) utilizes a standard row-column format with cell-embedded symbols to convey the proposed relative importance of a series of anthropogenic effects on an array of ecosystem elements, components, and levels of organization. This tabular conceptual model captures a large amount

Figure 2. Example of tabular conceptual model (Heathcote 1998).

Valued Ecosystem Components	Dredging	Infilling	Clearing, Site Preparation	Excavation, Tunneling, Blasting	Vehicle Operations	Diffuser Effluent	Combined Sewer Effluents	Air Emissions	Presence of Artificial Island
Terrestrial habitat	○	○	○	○	○				
Osprey	○	○		○	○				○
Great blue heron	○	○		○	○				
Air quality	—	○	—	○	○			○	
Marine benthic community	○	⊖		—	○	+	+		
Marine water quality	○	○		—	—	+	+		
Marine sediment quality	○	○		—	○	+	+		
Coastal physiography	—	○				○	○		○

— no impact
○ insignificant negative impact
+ significant negative impact
⊖ positive effect

Figure 10.4 Portion of environmental effects matrix used in the Halifax-Dartmouth Metropolitan Sewage Treatment System EA (adapted from Jacques Whitford Environment Ltd. 1992) of hypothetical information about the relationships between human activities and inherent ecosystem structure and function, but does not allow the user to understand assumptions of linearity or anything about scale-dependent feedback responses that could modify either human activities or ecosystem integrity.

Figure 3. Example of a tabular conceptual model (Williams et 1997).

TABLE 4.2.—Five classes of factors organize ecological systems and provide a framework for assessing biological integrity. In each class, some factors are marked (A) to indicate their special applicability to aquatic systems or (T) to terrestrial systems. (Adapted from Angermeier and Karr 1994.)

	Physicochemical conditions	
Temperature	Nutrients	Oxygen (A)
pH	Salinity	Contaminants
Insolation (sunlight)	Precipitation (T)	
	Trophic base (the food supply)	
Energy source	Standing stock (biomass)	Energy transfer efficiency
Productivity	Nutritional content of food	Complexity of trophic web (connected food chains)
Food particle size	Spatial distribution of food	
	Habitat structure	
Spatial complexity	Vegetation height (T)	Water depth (A)
Cover and refugia	Vegetation form (T)	Current velocity (A)
Topography (T)	Basin and channel form (A)	
Soil composition (T)	Streambed substrate (e.g., clay, gravel, bedrock) (A)	
	Temporal variation	
Seasonal	Fire	Weather (T)
Annual	Amplitude	Flow regime (A)
Climate change	Predictability	
	Biotic interactions	
Competition	Herbivory (consumption of living plants)	Coevolution
Parasitism	Mutualism (mutually beneficial relations among organisms)	
Predation		

In Figure 3, the tabular conceptual model of Williams et al. (1997) does not utilize a strictly defined row-column structure or any symbolism as described above. Rather, this model purports to represent generic ecosystem functioning (including both terrestrial and aquatic) by five primary classes of ecosystem "factors" that reflect some, but not necessarily complete, information about ecosystem structure, interactions, and temporal variability. Although this model varies in construct from Heathcote (1998), it likewise does not allow the user to understand assumptions of linearity or anything about scale-dependent feedback responses that could modify either human activities or ecosystem integrity.

<u>*Schematic conceptual models*</u> come in a seemingly unending, and sometimes alarming, variety; but for our purposes can be generally classified as 1) picture models, 2) box-arrow models [state-transition, hierarchical, input-output, and 3) matrix models.

Picture models are very illustrative and can devised in most any configuration to represent any reduced-form abstraction across a variety of temporal and spatial scales. Five examples are presented below (Figure 3-7).

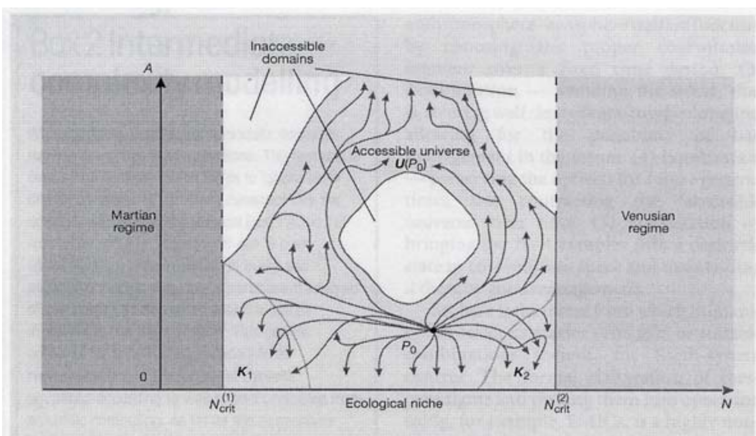


Figure 3 A 'theatre world' for representing paradigms of sustainable development. The space of all conceivable co-evolution states $P = (N, A)$ is spanned by a 'natural' axis, N (representing, say, global mean temperature) and a civilizatory axis, A (representing, say, global gross product). Vertical lines at $N_{crit}^{(1)}$ and $N_{crit}^{(2)}$ delimit the niche of subsistence states for humanity between an ultra-cold 'Martian regime' and an ultra-hot 'Venusian regime'. The domain $U(P_0)$ ('accessible universe') embraces all possible co-evolution states that can be reached from the present state P_0 by some management sequence from the overall pool. $U(P_0)$ contains specific 'catastrophe domains' K_1 and K_2.

Figure 4. Example of a universal-scale picture conceptual model that describes all conceivable evolutionary states and pathways that can be reached from the present (Schellnhuber 1999).

Figure 5. Example of three axis ordination picture conceptual model that purports, without any reference to scale, to represent broad sweeping generalization about the temporal dynamics of ecosystem resilience and transition as a function of system connectedness and integrity (Gunderson and Pritchard 2002). This model allows the user to comprehend sweeping and broad theoretical concepts without bogging the user down with scale-dependent details.

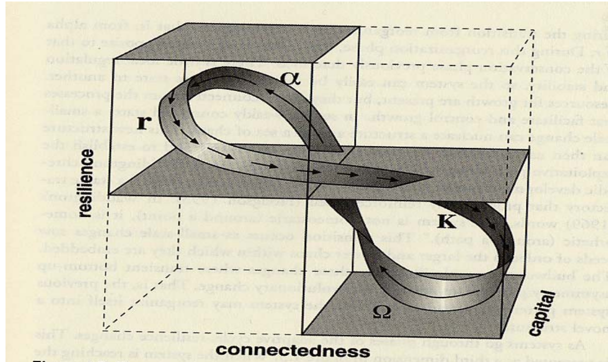


Figure 1.3. Ecosystem dynamics, indicating transitions among stages (r, K, Ω, α) and the resilience of each stage. The arrows show the speed of that flow in the cycle, arrows close to each other indicate a rapidly changing situation and arrows far from each other indicate a slowly changing situation. The cycle reflects changes in three attributes: x-axis, the degree of connectedness among variables, y-axis, the resilience of the system (low to high), and z-axis, the amount of accumulated capital (nutrients, carbon) stored in variables that are the dominant structuring variables at that moment in the system.

Figure 6. A simple polygon-structured picture conceptual model that purports to represent functional habitat types within a generic Pacific coast watershed. The nested polygons confer an understanding that when planning for considering watershed restoration, management prescriptions will likely vary according to the ecological importance and value attached to the variety of habitats types. While this picture reaffirms the importance of recognizing variation in ecological importance, it does not provide any substantive understanding of scale-dependent variability of ecosystem structure and function (Adams 2002).

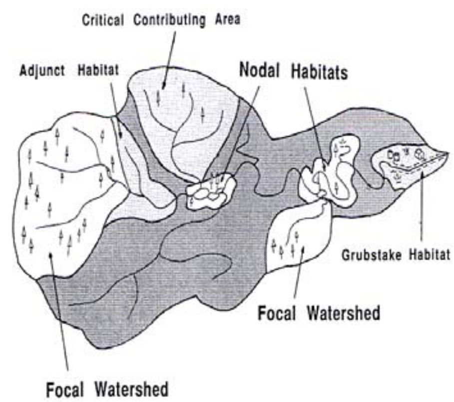
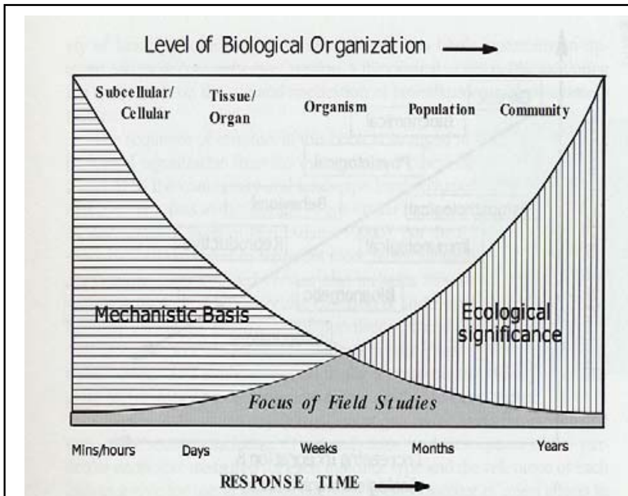


FIGURE 7.2.—Simple conceptual diagram depicting spatial relations between functional habitat types identified in the "rapid biotic and ecosystem response" strategy (Doppelt et al. 1993; Frissell et al. 1993), as it might be expressed in a typical Pacific coastal drainage basin.

Figure 7. A X-Y axis picture conceptual model that purports to represent the dynamic tradeoffs between the scope of mechanistic understanding and significance of ecological phenomenon. The X axis is conceptualized along a L->R continuum of increasing ecological complexity and time; with the Y axis unlabeled but from B->T representing increasing level of knowledge.



Figur 8. Another X-Y axis picture conceptual model that purports to represent a two dimensional continuum time and space variability of key ecological components and processes. This type of conceptual model allows the user to quickly comprehend the difficult concept of time x space, but the user cannot understand how much of the model is based on strong mechanistic understanding or hypothetical projections (Gunderson et al. 1995).

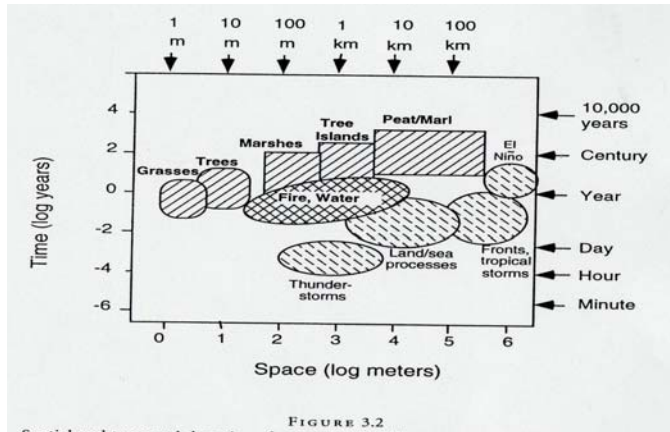


FIGURE 3.2
Spatial and temporal domains of vegetation/landform structures (squares), atmospheric variation (circles), and key processes (cross-hatched area) in the Everglades ecosystem.

Box-arrow conceptual models can also be presented in a variety of forms that can convey a variety of information of variable complexity. Three box-arrow conceptual models presented below (Figure 9-11) capture many of the preferable traits of such models.

Figure 9. A state-transition box-arrow conceptual model that is a classic reduced-form representation of the planetary ecology of Earth. This “wiring diagram of Earth is static and inconsistent and represents a tremendous level of censorship that cannot hope to allow the use to understand the effects of starfish population dynamics on the rise of atmospheric CO2 (Schellnhuber 2003).

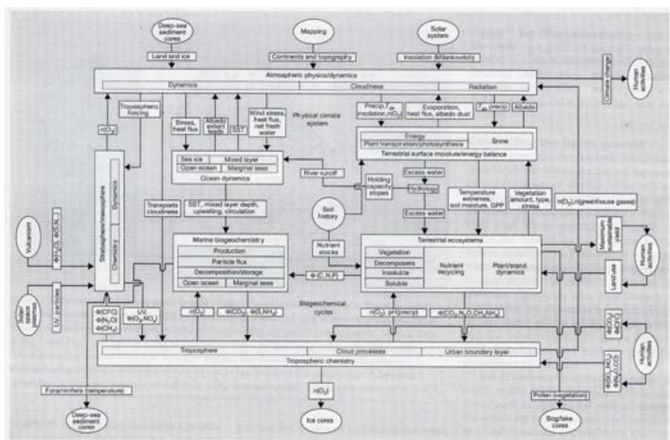
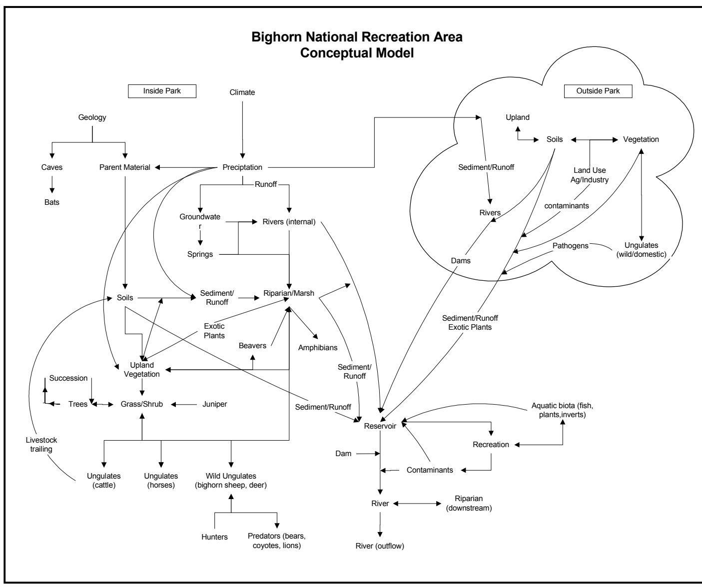


Figure 2 A simplistic conceptual model of the planetary machinery (reconstructed on the basis of ref. 14).

Figure 10. A box-arrow reduced-form conceptual model that displays hypothetical details of some of the internal and external factors and their linkages and interactions that underpin the BICA system (Patten 2002). Although this model does not allow the user to understand scale-dependent spatial or temporal dynamics, it does reinforce the importance of activities in the surrounding and upstream watersheds.



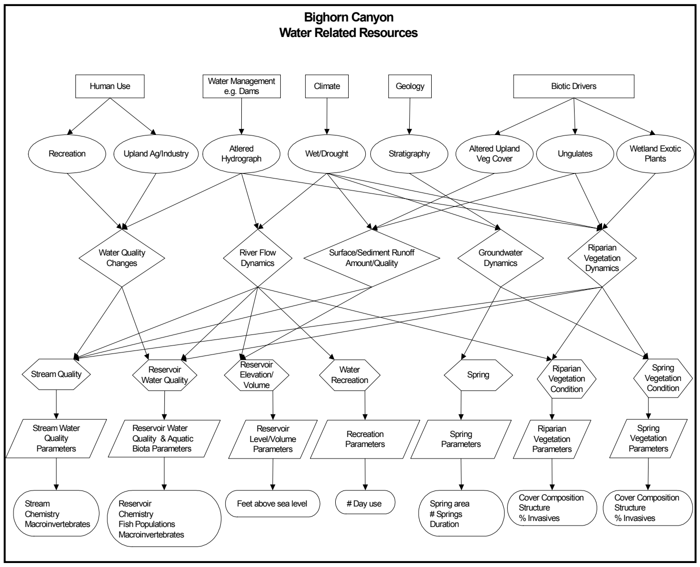


Figure 11. A hierarchical configured box-arrow conceptual model that shows a top to bottom one-way flowgram of ecological drivers/sources (rectangle), stressors (oval), effects (diamond), attributes (hexagram), and measures (parallelogram) (Patten 2002). This model shows water-related issues relative to streams and reservoir, and riparian and spring related parameters. Stressors include human activities in the upland and on the reservoir, upland land uses and changes, and changing climate and altered hydrology influenced from n and out of the park.

Input/Output - Matrix models are only variations from box-arrow models, as there are box-arrow models with indications of in- and outputs. A model for energy flow in an oyster reef community (Kcal $m^{-2}d^{-1}$) and storage (kcal m^{-2}) (Figure 12) can be considered to be an input/output matrix model (Grant 1997) where the matrix has a direct causal flow or interaction from compartment J (column) to compartment I (row) while expressing the probabilities that a substance in J will be transferred to I in one unit of time.

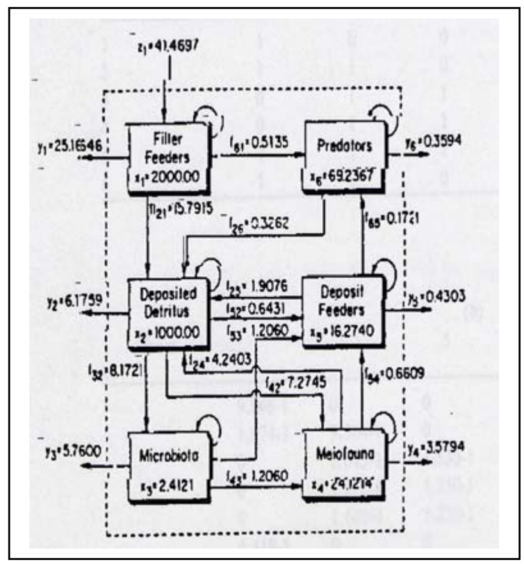
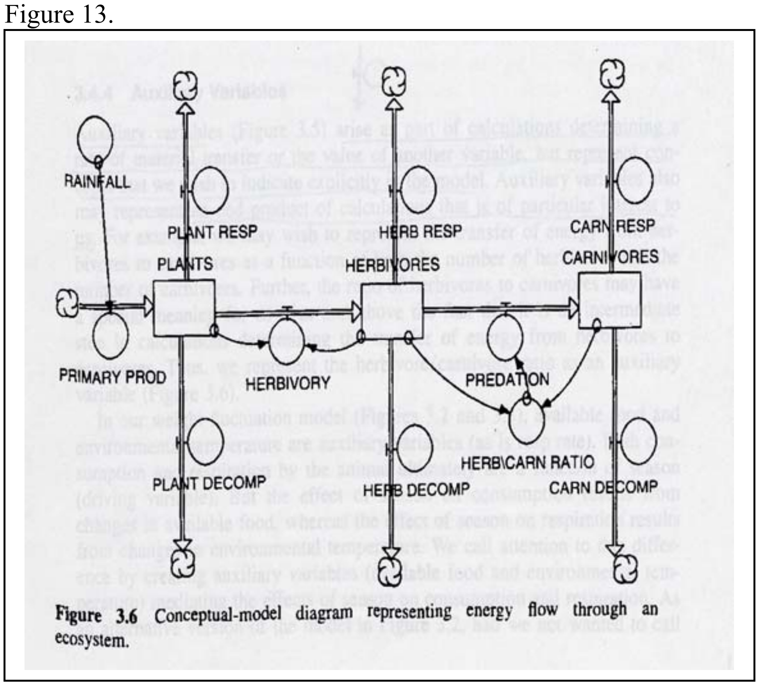


Figure 12.

Figure 13.



Input/output models often use a symbolic language where rectangles represent state variables, parameters or constants are small circles, sinks and sources are clouds, flows are arrows, and rate equations connect state variables to the flows. Figure 13 describes the transfer of energy from herbivores to carnivores as a function of the # of both [*sensu* wolf numerical response described above by Boyce (1999)].

How can conceptual models meet the needs of the NPS Vital Signs Monitoring Program?

Desirable Characteristics of a Vital Sign / Indicator. The development of conceptual models of park ecosystems involves the identification, inclusion, and scale-dependent linking of system variables such as drivers, stressors, effects, attributes, metrics (NPS 2003); state variables, constants, auxiliary variables, material transfers, sources and sinks (Grant et al. 1997), and other variables, often in a hierarchal form. It has been suggested that the inclusion of variables into conceptual models can take two forms (Jorgensen 1988, Grant et al. 1997). The first involves inclusion of a limited suite of model variables as simple as possible and subsequent iterative addition of critical components that were initially overlooked. The other approach is to include virtually all model components that could possible have any importance and then delete the superfluous ones (Grant et al. 1997). Given the inherent levels of uncertainty in ecosystem modeling, it is often better to use a slightly more complex model than a too simple approach. The criteria used for inclusion or exclusion of conceptual ecosystem model variables, thus provides the pool of variables that is drawn upon for the selection of ecological indicators that possess the desirable characteristics described below. Indeed, the desirable characteristics of conceptual model variables must then underpin those of ecological indicators. Grant et al. (1997) suggests that conceptual model variables and components have the following desirable characteristics: 1) *state variables* should represent vertices of accumulation of resources within an ecosystem (e.g. energy contained in plants, herbivores, predators); 2) *driving variables* should affect but not be affected by the rest of the system (e.g. transfer of energy from the sun to plants defines season within a year); 3) *constants* should not vary under assumptions of the conceptual model (e.g. coefficients that are part of a rate equation); 4) *auxiliary variables* arise out of calculation and should represent explicit model concepts; 5) *source and sink variables* represent origin and termination points of material transfers (e.g. energy) into and out of a system; 6) *material transfers* should describe quantitatively the flow of material (e.g. energy) between two state variables, between a source and a state variable, or between a state variable and a sink.

Fancy (2003) recently described a suite of top-to-bottom hierarchal conceptual model components including: *drivers/disturbances* that exert major forcing of large-scale influences on natural systems; *stressor/consequences* that cause significant changes in ecological components, patterns and relationships in natural systems; *ecological effects* that are responses to drivers and stressors; *attributes/indicators* that are any information rich living or non-living feature of an ecosystem that may be independent or integrative and can be measured or estimated and that provide insights into the state of the ecosystem; *measurements* that are specific measures of an attribute or indicator. Fancy (2003) states that indicators is often used synonymously with vital sign and are a selected subset of the physical, chemical, and biological elements and processes of natural systems that are selected to represent the overall health or condition of the system, known or hypothesized effects of stressors, or elements that have important human values. Vital signs/Indicators may occur at any level of organization including landscape, community, population, or genetic levels, and may be compositional (referring to the variety of elements in a system), structural (referring to the organization or pattern of the system), or functional (referring to ecological processes)(Fancy 2003).

Thus, a “vital sign” is a variable that is selected from the larger pool of “candidate” indicators, and meets or exceeds a parsimonious suite of desirable characteristics that underpin decisive functionality, feasibility, informational power, and cost-effectiveness. The suite of criteria that optimally characterize a desirable vital sign is a topic that has been discussed widely in the literature. In 1998, a NPS vital signs monitoring workshop identified 12 desirable characteristics of a vital sign or ecological indicator for long-term ecological monitoring. A vital sign: 1) has dynamics that parallel those of the ecosystem or component of interest, 2) is sensitive enough to provide an early warning of change, 3) has low natural variability, 4) provides continuous assessment over a wide range of stress, has dynamics that are easily attributed to either natural cycles or anthropogenic stressors, 5) is sensitive enough to provide an early warning of change, 6) is distributed over a wide geographical area and/or are very numerous, 7) are harvested, endemic, alien, species of special interest, or have protected status, 8) can be accurately and precisely estimated, 9) have costs of measurement that are not prohibitive, 10) have monitoring results that can be interpreted and explained, 11) are low impact to measure, and 12) have measurable results that are repeatable with different personnel (NPS 2003). Additionally, it has been acknowledged that a NPS vital sign should fit into one of three categories: a) those vital signs or indicators that are required to be included in a monitoring program for legal reasons (e.g. T&E species or items included in a park's enabling legislation); b) those that are required for Performance Management reporting purposes or because funding was provided for a specific purpose (e.g. impaired waters monitoring); or c) those selected from a list of recommended vital signs or identified as a priority (NPS 2003).

Angermeier (1997) states that for assessment of biological integrity, the ideal biological indicator is: 1) easy to measure and interpret; 2) sensitive to human impact prior to severe ecological damage; 3) sensitive to a wide range of impact types and levels; 4) able to distinguish between natural variation and impact-induced variation; 5) applicable over multiple regions; 6) helpful in identifying the cause of an ecological problem; and 7) meaningful to the public. Because no single indicator can capture and reflect upon the inherent complexity of wild land ecosystems, efforts such as the NPS Vital Sign Monitoring Program recommend utilization of suites of indicators as described by (Karr et al. 1986, Karr 1987; Fausch et al. 1990). Thus, a suite of indicators of biological integrity should a) have broad sensitivity to human impacts; b) represent multiple levels of ecological organization such as individual, population, community or landscape; and c) reflect key elements and processes (Angermeier 1997).

The characteristics that define indicator suitability must also reflect the context and purpose of the monitoring effort. Kershner (1997) described three types of natural resource monitoring for watershed management. *Implementation monitoring* should ask whether park management (as defined by park objectives) is being implemented properly and is would be designed to continually evaluate whether stated park management objectives are designed appropriately. This type of monitoring would likely apply strongly to adaptive management programs, wherein park management decisions are based on incomplete knowledge but where midcourse corrections can be implemented to adjust management outcomes. *Effectiveness monitoring* is often referred to as trend monitoring and attempts to estimate change (variability) over time that is then translated into quantifiable understanding of whether resource condition objectives are being met. This type of monitoring often requires some understanding of the physical, biological, and sometimes social factors that underpin ecosystem structure and function. *Validation monitoring* reflects a research motivation and is designed to generate explicit quantification of basic assumptions behind effectiveness monitoring. Thus validation monitoring is a research tool to examine the fundamental understanding of ecosystem structure and function (Kershner 1997). Incorporation of both validation and effectiveness monitoring is a vital component of any park-based adaptive management program. The use of ecological indicators in natural resource monitoring were similarly identified by Dale and Beyeler (2001) to 1) assess the condition of the environment (e.g. implementation monitoring); 2) diagnose the cause of environmental variability (e.g. validation monitoring); and 3) provide an early warning signal of changes in the environment (e.g. effectiveness monitoring).

Green (1979) described 10 principles of environmental field studies that can also be seen as guidelines for desirable characteristics of ecological indicators. Indicators should 1) be concise, coherent, and comprehensible; 2) be able to be measured through replicate sampling; 3) be representative (e.g. able to be measured with an equal number of randomly allocated replicate samples); 4) be able to demonstrate effect through comparison with a control; 5) be based on preliminary sampling that describe inherent variability; 6) describe what is being sampled with equal and adequate efficiency across the range of sampling conditions; 7) be applicable to a variety of scales of ecological organization; 8) be able to include appropriate size, density and distribution of samples; 9) be transparent so that data can be tested to see if error variation is homogenous, normally distributed, and independent of the mean; and 10) be sustainable and measurable over the long-term.

Dale and Beyeler (2001) state that a suite of ecological indicators should represent key information about ecosystem structure, function and composition. As Karr (1987) stated, Dale and Beyeler (2001) also propose that a suite of ecological indicators must capture the complexities of ecosystems but also remain simple enough to be routinely monitored. They recommend that the desirable indicators should: 1) be easily measured; 2) be sensitive to stresses on the system; 3) respond to ecosystem stressors in a predictable manner; 4) be anticipatory; 5) predict changes that can be averted by management action; 6) be integrative; 7) have a known response to disturbances, anthropogenic stressors, and changes over time; 8) have low response variability; 9) be able to provide information relevant to another scale; 10) transparently reflect management long-term goals and objectives; and 11) arisen from a deliberate and defined protocol for identification of indicators. *Easily measured indicator* metrics should be easy to understand, simple to apply, and provide information that is relevant, quantitatively sound, easily documented and cost-effective. E.g. the proverbial coal mine canary (Stork et al. 1997, Lorenz et al. 1999).

The desirable characteristics of an ecological indicator described by Dale and Beyeler (2001) above can be translated into more focused indicator titles as follows. *Stress sensitive indicators* should display high sensitivity to particular, and perhaps subtle, stressors, thereby serving as an early warning signal of reduced system integrity (Karr 1991). *Stress predictable indicators* should be unambiguous and predictable even if responding to gradual rates of stress. *Anticipatory indicators* should reflect a threshold response dynamic wherein an observed response occurs prior to an important reduction in system integrity (e.g. the canary should die before the miner). *Predictive management indicators* should be scale-dependent and reflect the real temporal and spatial scales of management capabilities. Predictive management indicators cannot anticipate ecological catastrophes such as volcanoes or hurricanes. *Integrative indicators* should behave predictably across appropriate scales and can be aggregated to provide assessment of multi-scale systems (Brooks et al. 1998). *Mechanistic indicators* have a known functional response to ecosystem disturbances and stressors. These indicators have been adequately studied and the mechanisms of ecosystem response are well known. *Minimal variability indicators* should have a small range of variability of response to known stressors that can be distinguished from inherent background ecosystem range of natural variability.

Revenga et al. (1998) have attempted to provide a quantitative basis for integrated conservation management so as to gauge the nature and patterns of threats to watershed globally. They analyzed data from 145 watersheds around the world and presented 15 indicators grouped into three main themes: *Watershed value* – fish species richness and endemism, endemic bird areas, aridity, population density, and water scarcity; *Watershed condition* – landscape modification, irrigated cropland, existing major dams, remaining original forest, extent of forest loss, and soil erosion from water; and *Future Vulnerability* – urban population growth, tropical deforestation, planned major dams, and level of protection. Although Revenga et al. (1998) did not explicitly describe the criteria or process they employed to identify and select these indicators, they clearly placed a higher value on indicators that are 1) measurable and based on some knowledge of the historic range of variability (e.g. forest cover, fish sp. richness, population growth); and 2) management relevance (e.g. proposed new dams, level of protection/management). It is unclear whether Revenga et al. (1998) examined monitoring feasibility, efficiency or sampling adequacy.

During the late 1990s, the Ecological Monitoring and Assessment Network (EMAN) of Canada spent considerable effort in developing a suite of core variables that can be utilized to monitor the condition of natural resources across Canada and provide early warning of ecosystem change (Environment Canada 2000). These "core variables" can be viewed synonymously with vital signs and so the criteria utilized by Environment Canadian should have applicability to NPS efforts. There are eight primary EMAN criteria for a vital sign: 1) addresses one or more environmental themes and issues; 2) monitoring data may be related to an ecosystem moving out of its normal range of resilience that may lead to degradation; 3) is sensitive; 4) integrates ecosystem stresses over space and time; 5) is sufficiently valid and accepted; 6) can be used over a wide range of climatic, soil, topographic and vegetation conditions; 7) is cost-effective; and 8) can be implemented by anyone with appropriate training and/or using a detailed protocol.

An assessment of biological indicators of aquatic ecosystem stresses led Adams (2002) to conclude that the term "ecological indicator" is too general and should be reduced to yield more appropriate specificity. Adams (2002) proposes that there is meaningful distinction between "b*iocriteria*", "*biomarkers*", and "*bioindicators*." A *biocriteria* is defined within the context of regulatory processes at the population or community level and could include indices of the numbers and kinds of organisms present in an aquatic system of interest such as an index of biotic integrity (IBI), stream condition index (SCI), invertebrate community index (ICI) or the biological monitoring working party score (BMWP). Biomarkers are considered as functional measures of exposure to environmental stressors that are usually expressed at suborganismal level of organization such as molecular, biochemical and even physiological endpoints (Adams 2002). Bioindicators are defined as either structural entities such as sentinel species (Van Gestel and Van Brummelen 1996), or they can be functionally biological endpoints at higher levels of organization (Adams 1990, Engle and Vaughn 1996). Adams (2002) suggests that the desirable characteristics of a biomarker or bioindicator are 1) sensitivity and specificity to stressors; 2) relationship to cause; 3) response variability; 4) temporal scales of response; and 5) ecological or biological significance, but that degree of relevance of these criteria varies between biomarker and bioindicator (Table xx1). Generally, increasing levels of biological organization result in decreasing mechanistic understanding but increasing levels of ecological relevance (Figure 1). Thus, Adams (2002) recommends that ultimately, long-term monitoring of ecosystems should include a selected suite of measures (e.g. vital signs) along the continuum of levels of ecological organization where meso-scale responses centered near the organismal level provides the central focus through which mechanistic understanding and ecological relevance can be coupled.

Recently, the U.S. Environmental Protection Agency's Office of Research and Development published a suite of evaluation guidelines for ecological indicators (Jackson et al. 2000) that include 15 recommended guidelines (see Table xx2) for the identification and selection of relevant ecological indicators that are organized around four crucial questions: 1) Is the potential indicator relevant to management concerns and to the ecological resource or function at risk?; 2) Is the potential indicator sampling methodology feasible, appropriate, and efficient for use in a long-term ecological monitoring program?; 3) Are the errors of measurement and range of natural variability over the relevant temporal and spatial scales sufficiently understood and documented?; 4) Will the indicator convey information on ecological condition that is relevant to resource decision-making?. Kurtz et al. (2001) summarized that these EPS guidelines are intended to provide a flexible yet consistent framework for indicator review, comparison, selection, and to provide direction for research on indicator development. The EPA states that the guidelines should not be viewed as criteria that can determine indicator applicability or effectives. Rather, these 15 guidelines can provide a framework for asking relevant questions about indicator relevance, feasibility, variability, and utility. (Kurtz et al. 2001).

<u>Applicability of Conceptual Models in the Near-term.</u> In the very near-term, NPS networks need to be able to comprehend the relevant structure and function of multiple levels of ecological organization of important park ecosystems and translate this understanding of ecological organization into identification of vital signs (ecological indicators) through deliberate and transparent decision support systems to identify the of environmental health in parks. To achieve these outcomes, conceptual models need to be viewed as problem solving vehicles underpinned by narrative literature review that provides the reliable knowledge basis for conceptual modelling. Further, a variety of conceptual models (narrative, tabular and schematic) will need to be developed and linked to deliberate and transparent decision support systems (DSS) that will allow the qualitative and quantitative information that can be derived from conceptual models to be processed (continuous or categorical filtering and rank-ordering) to generate suites of vital signs or ecological indictors. To date, no single vital sign selection DSS has been recommended by the NPS to meet all the needs of the various networks.

To assist users to understand the variability in usefulness of conceptual models, I employed a simple row-column tabular conceptual configuration in Table 1 below to present my understanding (according to a relativistic scale of low, medium and high) of how well seven types of conceptual models present meaningful information that can be used to address six NPS programmatic needs and 35 desirable characteristics of vital signs or ecological indicators. The information in Table 1 suggests that narrative and tabular conceptual models have the widest and schematic models have the narrowest applicability to address programmatic outcomes or desirable characteristics of vital sign criteria. Simple picture conceptual models have the power to convey broad and sweeping concepts but often fail to relate sufficient knowledge detail that can be directed at vital sign selection processes. Multiple-axis picture models seem to be reasonable good at presenting both general concepts as well as more detailed quantitative understanding of scale-dependent ecosystem temporal and spatial dynamics. In general, the array of box-arrow models seem to have only limited applicability to selection of vital signs. However, box-arrow hierarchical models seem to have strong intuitive appeal and applicability to the objective of comprehending the relevant structure and function of multiple levels of ecological organization of important park ecosystems. The utility of box-arrow hierarchical models for this objective is scale-dependent. If the modeler selects too fine or coarse a scale, then the information presented may be irrelevant. By default then, a meso-scale will become the most utilitarian scale of such models. Tabular and narrative models, underpinned by narrative literature review, also seem to be able to convey the most important information and knowledge basis for evaluating potential vital signs against a suite of desirable criteria, regardless of whether the criteria relate to conceptual relevance, feasibility of implementation, response variability, or interpretation and utility.

Applicability of Conceptual Models in the long-term. In the long-term, we need to be able to 1) comprehend the range of natural (e.g. evolutionary) variability and ecological thresholds of dynamic "vital" ecological parameters and translate this understanding into deliberate and transparent long-term monitoring protocols capable of adequately detecting important departures from natural range of variability; and 2) comprehend the range of anthropogenic-induced ecosystem variability that overlays the range of natural (e.g. evolutionary) variability and ecological thresholds of dynamic "vital" ecological parameters and translate this understanding into deliberate and transparent adaptive management alternatives for park managers to attempt mitigation. These objectives will be driven primarily by quantitative information derived from field surveys and monitoring. However, since quantification is the process by which science tries to build a conceptual basis for understanding the complexities of reality, our quantification will always be imperfect. Hence, there will must be a long-term role and function for a full complement of conceptual models to project and comprehend the complexities of ecological thresholds and anthropogenic-induced ecosystem variability.

Literature Cited

Adams, S.M. 2002. Biological indicators of aquatic ecosystem stress. American Fisheries Society, Bethesda, MD.644 pp.

Angermeier, P.L. 1997 Conceptual roles of biological integrity and diversity. Pp: 49-65. In: Williams, J.E. C.A. Wood, and M.P. Dombeck, eds. Watershed Restoration Principles and Practices. American Fisheries Society, Bethesda, MD. 559 pp.

Boyce, M. 1999. Multi-trophic level ecology of wolves, elk and vegetation in Yellowstone National Park 2000-2004. Proposal on file, Yellowstone NP.

Brooks, R.B., T.J. O'Connell, D.H. Wardrop, L.E. Jackson. 1998. Towards a regional index of biological integrity: the example of the forested riparian ecosystem. Environmental Monitoring and Assessment. 51:131-143.

Christie, M.J. 1990. Aboriginal science for the ecologically sustainable future. Batchelor Journal of Aboriginal Education 4:56-68.

Dale, V.H. and S.C. Beyeler. 2001. Challenges in the development and use of ecological indicators. Ecological Indicators. 1:3-10.

Environment Canada. 2000. Selecting core variables for tracking ecosystem change at EMAN sites. Final consultants report prepared by Geomatics International, Inc. Guelph, Ontario, for Environment Canada, EMAN Coordinating Office, Burlington, Ontario, Canada. http://www.eman-rese.ca.

Fausch, K.D., J. Lyons, J.R. Karr, and P.L Angermeier. 1990. Fish communities as indicators of environmental degredation. Pp. 123-144 in S.M. Adams, ed. Biological indicators of stress in fish. American Fisheries Society Symposium 8, Bethesda, MD.

Grant, W.E., E.K. Pedersen, S.L. Marin. 1997. Ecology and natural resource management: Systems Analysis and Simulation. John Wiley & Sons, Inc., New York.

Green, R.H. 1979. Sampling design and statistical methods for environmental biologists. Wiley, New York.
Gunderson, L.H., C.S. Holling, and S.S. Light. 1995. Barriers and bridges to the renewal of ecosystems and institutions. Columbia University Press.
Gunderson, L.H. and L. Pritchard, Jr. 2002. Resilience and the behavior of large-scale systems. Scientific Committee on Problems of the Environment (SCOPE), Paris, France.
Fancy, S. 2003. Conceptual models: one approach. Unpublished manuscript. NPS. Washington D.C. (on file at Greater Yellowstone Network office, Bozeman, MT).
Heathcote, I. W. 1998. Integrated Watershed Management Principles and Practice. John Wiley & Sons, Inc., New York.
Jackson, L.E., J.C. Kurtz, and W.S. Fisher, eds. 2000. Evaluation guidelines for ecological indicators. EPA/620/R-99/05. U.S. Environmental Protection Agency, Office of Research and Development, Research Triangle Park, NC. 107pp.
Karr, J.R., K.D. Fausch, P.L. Angermeier, P.R. yant, and I.J. Scholosser. 1986. Assessing biological integrity in running waters: a method and its rationale. Illinois Natural History Survey Special Publication #5.
Karr, J.R. 1987. Biological monitoring and ecological assessment: a conceptual framework. Environmental Management 11:249-256.
Karr, J.R. 1991. Biological integrity: a long neglected aspect of water resources management. Ecological Applications. 1:66-84.
Kershner. J.L. 1997. Monitoring and adaptive management. Pp: 116-131. In: Williams, J.E. C.A. Wood, and M.P. Dombeck, eds. Watershed Restoration Principles and Practices. American Fisheries Society, Bethesda, MD. 559 pp
Kurtz, J.C., L.E. Jackson, and W.S. Fisher. 2001. Strategies for evaluating indicators based on guidelines from the Environmental Protection Agency's Office of Research and Development. Ecological Indicators 1:49-60.
Lorenz, C.M., A.J. Gilbert, W.P. Cofino. 1999. Indicators for transboundary river basin management. Pp:313-328. In: Pykh, Y.A., D.E. Hyatt, and R.J.M Lenz (eds.). Environmental indices: System Analysis Approach. EOLSS Publishers Co. Ltd., Oxford, UK.
National Park Service. 2003. Guidelines for Monitoring Natural Resources in our National Parks. NPS Intranet Website. http://www.nature.nps.gov/im/monitoring/index/htm
Patten, D. 2002. Chapter 3, Phase 1 Report of the Greater Yellowstone Network Vital Signs Monitoring Program. On file, Yellowstone NP.
Plumb, G.E., et al. 2003. Draft Chapter 3. Phase 2 Report of the Greater Yellowstone Network Vital Signs Monitoring Program. On file, Yellowstone NP.
Revenga, C., S. Murray, J. Abrammovitz, and A. Hammond. 1998. Watersheds of the world: Ecological value and vulnerability. A joint publication by the World Resources Institute and Worldwatch Institute. Washington D.C.
Schellenhuber, H.J. 1999. Earth system analysis and the second Copernican revolution. Nature 402:19-23.
Stork, N.E., T.J.B. Boyle, V.H. Dale, H. Eeley, B. Finnegan, M. Lawes, N. Manokaran, R. Prabhu, and J. Soberon. 1997. Criteria and indicators for assessing the sustainability of forest management: Conservation of biodiversity. Center for International Forestry Research. Working Paper No. 17, Bogor, Indonesia (cited in Dale and Beyeler, 2001).
Williams, J.E., C.A. Wood, M.P. Dombeck. 1997. Watershed Restoration: Principles and Practices. American Fisheries Society. Bethesda, MD.

Table 1. GRYN Coarse and Fine Filter Ecological Indicator Criteria

COARSE FILTER	FINE FILTER
Conceptual Relevance	**Conceptual Relevance**
1. Indicator structural or functional dynamics reflects relevance to ecosystem or component of interest	1. Indicator is harvested, endemic, alien, species of special interest, or have protected status
2. Indicator transparently reflects management long-term goals and objectives	2. Indicator is meaningful to the public
3. Indicator applies to a variety of scales of ecological organization	3. Indicator is integrative
	4. Indicator provides relevant information that is applicable to multiple scales of ecological organization
	5. Indicator is responsive to a relevant assessment question
	6. Indicator is applicable to both terrestrial and aquatic systems
Feasibility of Implementation	**Feasibility of Implementation**
4. Indicator measurement is not cost prohibitive	7. Indicator monitoring methodology already exists in scientific literature
5. Indicator measurement impacts must meet NPS standards	8. Indicator is distributed over a wide geographical area and/or is very numerous
6. Indicator measurement can be sustained over the long-term	9. Indicator can be accurately and precisely estimated (low error) across a range of sampling conditions
	10. Indicator is easy to measure and has measurable results that are repeatable with different personnel
	11. Indicator can be measured through replicate sampling with an equal number of randomly allocated replicate samples that are independent
	12. Indicator can be measured by appropriate size, density and distribution of samples
	13. Indicator monitoring design and measurements are appropriate for the spatial scale of analysis
	14. Indicator data management and quality assurance will be compatible with existing relevant info mgt system standards
Response Variability	**Response Variability**
7. Indicator is anticipatory and is sensitive enough to provide an early warning of change	15. Indicator has a rapid indicator lag time indicative of changes in ecosystem integrity
8. Indicator responds to ecosystem stressors in a predictable manner and has high signal-to-noise ratio	16. Indicator has low natural variability
	17. Indicator has low response variability
	18. Indicator is sensitive to small changes in the environment
	19. Indicator response thresholds for system degradation are known
	20. Indicator is sensitive to a wide range of impact types and levels
	21. Indicator is sensitive to stresses beyond historic range of variability
	22. Indicator provides continuous assessment over a wide range of impact types and levels

	23. Indicator is based on preliminary sampling that describes inherent variability
	24. Indicator has a known response to disturbances, anthropogenic stressors, and changes over time
	25. Indicator must exhibit significantly different responses among sites along a known condition gradient
	26. For integrative indicators, response variability of multiple measurements should be adequate
	27. Indicator data can be tested to see if error variation is homogenous, normally distributed, and independent of the mean
	28. Indicator temporal response variability within and across years can be understood
	29. Indicator spatial response variability is understood and can be partitioned
	30. Indicator historic databases are well established and baseline conditions are already known
Interpretation and Utility	**Interpretation and Utility**
9. Indicator is anticipatory of ecosystem degradation that can be mitigated by management action	31. Indicator is helpful in identifying the causal mechanism of an ecological response
10. Indicator responses and results are concise, coherent, and comprehensible	32. Indicator measurements and interpretation can demonstrate effect through comparison with a control
11. Indicator measurements and results can be clearly understood by scientists, publics, and policy makers	33. Indicator responds to ecosystem stressors in a predictable manner with known statistical power and low chance of type 2 errors
	34. Indicator response dynamics can be distinguished between natural variation and anthropogenic impact-induced variation
	35. Indicator provides information relevant to another temporal or spatial scale

Table 2. Relativistic scoring of how useful eight types of conceptual models may be in presenting meaningful information that can be used to address six programmatic needs and 35 desirable characteristics of vital signs or ecological indicators.

	Informal or Formal Narrative	Tubular	Picture x-y-z axis	Picture Simple	Box-arrow State-transition	Box-arrow hierarchical	Box-arrow In-out / Matrix
NPS Vital Signs Monitoring Program Outcomes (6)	**33% H 67% M 0% L**	**83% H 17% M 0% L**	**33 % H 33% M 33% L**	**0% H 0% M 100% L**	**33 % H 33% M 33% L**	**17% H 17 % M 66 % L**	**0 % H 83% M 17 % L**
1. Comprehend the relevant structure and function of multiple levels of ecological organization of important park ecosystems (Knowledge).	M	M	M	L	L	H	L
2. Translate understanding of ecological organization through deliberate and transparent decision support systems to identify the vital signs (ecological indicators) of environmental health in parks (Action).	H	H	L	L	L	L	M
3. Comprehend the range of natural (e.g. evolutionary) variability and ecological thresholds of dynamic "vital" ecological parameters (Knowledge).	M	H	H	L	H	M	M
4. Translate understanding of thresholds of natural variability into deliberate and transparent long-term monitoring protocols capable of adequately detecting important departures from natural range of variability (Action).	H	H	M	L	M	L	M
5. Comprehend the range of anthropogenic-induced ecosystem variability that overlays the range of natural (e.g. evolutionary) variability and ecological thresholds of dynamic "vital" ecological parameters (Knowledge).	M	H	H	**L**	H	L	M
6. Translate understanding of anthropogenic-induced ecosystem variability into deliberate and transparent adaptive management alternatives for park managers to attempt mitigation (Action).	M	H	L	L	M	L	M
GRYN Fine Filter Vital Sign or Ecological Indicator Criteria	**91% H 9% M 0% L**	**94% H 6% M 0% L**	**20% H 43% M 37% L**	**11% H 29% M 60% L**	**0% H 23% M 77% L**	**6% H 6% M 88% L**	**3% H 54% M 43% L**
Conceptual Relevance							
1. Indicator is harvested, endemic, alien, species of special interest, or have protected status	H	H	L	L	L	M	L
2. Indicator is meaningful to the public	H	H	M	H	L	L	L
3. Indicator is integrative	M	M	H	M	L	L	H
4. Indicator provides relevant information that is applicable to multiple scales of ecological organization	M	M	M	L	L	H	M
5. Indicator is responsive to a relevant assessment question	H	H	L	L	L	M	L
6. Indicator is applicable to both terrestrial and aquatic systems	H	H	L	H	L	M	L
Feasibility of Implementation							
7. Indicator monitoring methodology already exists in scientific literature	H	H	L	L	L	L	L
8. Indicator is distributed over a wide geographical area and/or is very numerous	M	H	M	M	M	H	L
9. Indicator can be accurately and precisely estimated (low error) across a range of sampling conditions	H	H	M	L	L	L	L
10. Indicator is easy to measure with results that are repeatable with different personnel	H	H	L	L	L	L	L

Continued.	Informal or Formal Narrative	Tubular	Picture x-y-z axis	Picture Simple	Box-arrow State-transition	Box-arrow hierarchical	Matirx
11. Indicator can be measured through replicate sampling with an equal number of randomly allocated replicate samples that are independent	H	H	L	L	L	L	L
12. Indicator can be measured by appropriate size, density and distribution of samples	H	H	L	L	L	L	L
13. Indicator monitoring design and measurements are appropriate for the spatial scale of analysis	H	H	M	L	L	L	L
14. Indicator data management and quality assurance will be compatible with existing relevant info mgt system standards	H	H	L	L	L	L	L
Response Variability							
15. Indicator has a rapid indicator lag time indicative of changes in ecosystem integrity	H	H	L	L	L	L	L
16. Indicator has low natural variability	H	H	M	L	L	L	L
17. Indicator has low response variability	H	H	H	L	M	L	L
18. Indicator is sensitive to small changes in the environment	H	H	H	L	M	L	L
19. Indicator response thresholds for system degradation are known	H	H	L	L	L	L	L
20. Indicator is sensitive to a wide range of impact types and levels	H	H	M	L	L	L	M
21. Indicator is sensitive to stresses beyond historic range of variability	H	H	M	M	M	L	M
22. Indicator provides continuous assessment over a wide range of impact types and levels	H	H	M	M	M	L	L
23. Indicator is based on preliminary sampling that describes inherent variability	H	H	L	L	L	L	M
24. Indicator has a known response to disturbances, anthropogenic stressors, and changes over time	H	H	M	H	L	L	L
25. Indicator must exhibit significantly different responses among sites along a known condition gradient	H	H	H	H	L	L	L
26. For integrative indicators, response variability of multiple measurements should be adequate	H	H	H	M	L	L	M
27. Indicator data can be tested to see if error variation is homogenous, normally distributed, and independent of the mean	H	H	L	L	L	L	M
28. Indicator temporal response variability within and across years can be understood	H	H	H	M	M	L	M
29. Indicator spatial response variability is understood and can be partitioned	H	H	M	M	M	L	M
30. Indicator historic databases are well established and baseline conditions are already known	H	H	L	L	L	L	L
Interpretation and Utility							
31. Indicator is helpful in identifying the causal mechanism of an ecological response	H	H	M	M	M	L	M
32. Indicator measurements and interpretation can demonstrate effect through comparison with a control	H	H	M	M	L	L	L
33. Indicator responds to ecosystem stressors in a predictable manner with known statistical power and low chance of type 2 errors	H	H	M	L	L	L	M
34. Indicator response dynamics can be distinguished between natural variation and anthropogenic impact-induced variation	H	H	M	M	L	L	L
35. Indicator provides information relevant to another temporal or spatial scale	H	H	H	M	L	L	L